Chapter 178

Frequency and probability of occurrence of clearness index for the region of Maceió-Alagoas

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ABSTRACT
Solar radiation is essential because its distribution around the planet establishes the variations of all the meteorological elements, determining the atmospheric and oceanic circulation patterns and configuring the terrestrial climate, besides being currently widely used for the production of alternative energy. Thus, the objective of this work is to analyze the solar radiation through frequency and probability of occurrence of clearness index in different seasonal periods for the region of Maceió, state of Alagoas. The RG was obtained from data from the INMET automatic stations for the city of Maceió, from January 2014 to December 2017. The Ro was calculated through the solar constant, vector radius of the Earth's orbit and zenith angle. KT was calculated by the ratio of RG to Ro. Histograms of frequencies and accumulatedfrequencies of KT were made. For the seasonal analysis of the solar radiation and KT conditions the data were separated in different seasonal periods. The hourly frequency of KT observed in the dry and rainy season had the highest occurrence in partially cloudy sky conditions, with an average of 53.62% of the total values for both seasons. The frequency of daily KT for the seasons had higher occurrence in partially cloudy sky conditions with an average of 79.74% of the data and the probability of annual occurrence was also higher for partially cloudy sky conditions with 57.21% for the values and 83.29% for daily values.

Keywords: Solar radiation, Renewable energy, Solar irradiance, Characterization.

1 INTRODUCTION

Among all the energy sources currently used by mankind, solar radiation is configured as the main one, and its distribution around the planet is essential, since it establishes the variations of all the meteorological elements that turn ends up determining the patterns of atmospheric and oceanic circulation and shaping the terrestrial climate (SOUZA, 1997). Moreover, solar radiation is important for contributing to changes in physical, chemical and biological processes in all ecosystems on Earth (SOUZA; NICÁCIO; MOURA, 2005; MONTERO, 2009). The knowledge of its availability in a surface and its local and seasonal variation has great relevance for the study and research in several areas such as meteorology, agriculture, geography, engineering, hydrology, etc. However, nowadays, both in Brazil and worldwide, solar radiation has its main focus on the production of alternative energy, in view of the increase in energy demand together with the possibility of reducing the supply of conventional fuels and the growing concern with the preservation of the environment (MARTINS et al., 2007; JACOVIDES, 2006). With this in mind, many researchers have conducted analysis and mapping of locations with greater use of solar energy, either outside or inside urban centers, in an effort to contribute to the installation of possible photovoltaic solar energy systems (e.g.: AMARANTE et al., 2019).

The radiation emitted by the Sun is made up of electric and magnetic waves and is therefore also known as electromagnetic radiation. The total radiation emitted by the Sun that reaches the top of the Earth's atmosphere is known as solar irradiance at the top of the atmosphere (Ro) (LIOU, 1980). Ro has no interference from the atmosphere and is affected only by solar emission, mean Earth-Sun distance, solar elevation, and wavelength. The solar constant (So), which is equivalent to 1367 W m-2, was adopted as the average reference value of Ro. Ro is very important for studies of radiation balance, climate and general circulation of the atmosphere (VAN HEMELRIJCK; VERCHEVAL, 1981). Part of the solar radiation that reaches the Earth's surface is called global solar irradiance (GIR). This irradiance is the main component of the Earth's energy balance, without it water would not exist, as well as, of course, the clouds and all life on the planet.

The RG is formed by two components, the direct solar irradiance (RD) which is the part that reaches the Earth's surface without atmospheric attenuation and the diffuse solar irradiance (Rd) originated from the scattering of solar radiation by atmospheric constituents before reaching the Earth's surface. So, it can be seen that not all solar radiation that reaches the top of the atmosphere reaches the surface, part is scattered, another part is reflected or absorbed in the atmosphere. Among the various atmospheric constituents water vapor is one of the main contributors to the process of attenuation of solar radiation in the atmosphere. Thus, the global atmospheric transmittance (KT) that is determined by the ratio between RG and Ro, represents the effective amount of solar radiation that reaches the Earth's surface. The KT varies throughout the day due to the thickness of the atmosphere to be crossed by solar rays with lower values at sunrise and sunset, and higher near local noon (PEREIRA; ANGELOCCI; SENTELHAS, 2002).

Through the values of KT it is also possible to establish which periods of the year, in a given location, have higher incidence of global solar radiation, thus determining the cloudiness conditions, i.e., the amount of clouds that is present in the region. Thus, when KT values are high, possibly the cloudiness levels are low, i.e. the sky has a minimum amount of clouds or no clouds at all. When the KT values are low, the opposite occurs, cloudiness levels increase. Despite its great relevance in determining the solar radiation at the surface, there are still few studies focused on its analysis and the existing ones need better characterizations or to be updated (e.g. Porfirio et al., 2012), but even so, they contribute significantly to the literature. The lack of related work occurs possibly due to complications in the measurement of global solar radiation, necessary for the calculation of KT, which are difficult to be performed in Brazil and even more so in the state of Alagoas, either because of the cost of equipment maintenance or errors from technical failures and problems related to the operation of equipment (MORADI, 2009).

Population growth has required an increase in consumption levels, especially in the energy area, and this high consumption requires an increasing production of electricity. In the state of Alagoas, the situation is decadent, as electricity production in the state has been decreasing in recent years (EMPRESA DE PESQUISA ELÉTRICA, 2017). Thus, several researchers and developers are looking for reliable solar radiation data either for analyzing their local distributions or for developing models aimed at evaluating and simulating their availability for a given area (BERTRAND; VANDERVEKEN; JOURNÉE, 2015; GARRISON, 1985), which are essential for the implementation of photovoltaic energy systems.

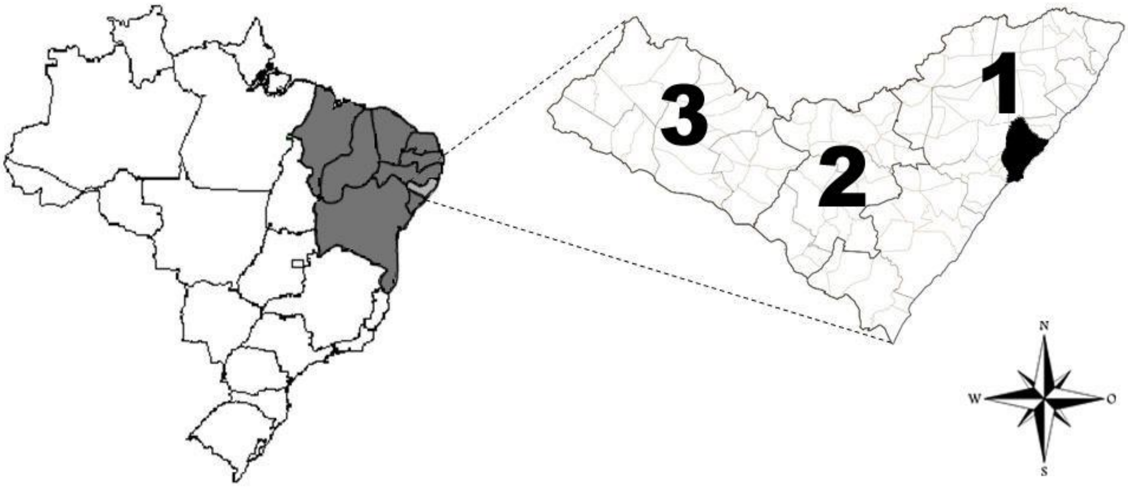
Thus, the present work aims to analyze the solar radiation through statistical frequency and probability of occurrence of global atmospheric transmittance in different seasonal periods for the region of Maceió, state of Alagoas.

2 MATERIAL AND METHODS

2.1 CHARACTERIZATION OF THE STUDY AREA

The study area is located in the city of Maceió, state of Alagoas - Brazil (Fig. 1). Maceió is the capital of the state of Alagoas, located in the Northeast region of Brazil, with an estimated population of over one million inhabitants in 2018 (IBGE, 2018). The state of Alagoas is located in the east of the Northeast region, bordering the states of Pernambuco (to the north), Bahia and Sergipe (to the south) and the Atlantic Ocean (to the east). It is subdivided into three geographical mesoregions (Litoral/Zona da Mata, Agreste, and Sertão), possessing different types of climate.

Figure 1. Geographic location of the Brazilian Northeast (in dark gray), the state of Alagoas with its mesoregions, Litoral (1), Agreste (2) and Sertão (3) and the municipality of Maceió (highlighted). Source: Adapted from Lopes Júnior (2017).



The mesoregions of Litoral/Zona da Mata and Agreste have a hot and humid climate, with annual precipitation varying from 600 - 3000 mm, the rainy season is concentrated between autumn and winter (April to July), with 55.2% of the total precipitation expected in the year and the dry season occurs between spring and summer (November to February) with only 12.5% of the total (LIMA, 1991; SOUZA E LIMA, 1995; MOLION E BERNARDO, 2002). The mesoregion of Sertão has a drier climate with low precipitation, summer and autumn are the seasons corresponding to the rainy period and winter with lower accumulated precipitation (REBOITA et al., 2012). The state's precipitation regime is associated with the various meteorological systems common in much of Northeast Brazil. Among the main systems are the coastal instability lines, seasonal variation of trade winds, position and intensity of the Intertropical Convergence Zone (ITCZ), High Level Cyclonic Vortices (HVCAN), East Waves (OL), as the main ones (SOUZA et al., 2003).

The city of Maceió is located on the Alagoas coast, having a rainy tropical climate with dry summer according to the Köppen classification (EMPRAPA, 2012). According to the latest climatological normal of the National Institute of Meteorology (INMET) for the city of Maceió referring to the period from 1981 to 2010, the average annual temperature is 25.1°C, while for the dry season (November to February) is 25.95 °C and for the rainy season (April to July), 24.68 °C. The average annual accumulated precipitation value is 1867.4 mm. For the dry season 243.4 mm and for the rainy season 1123.4 mm (INMET 2018).

2.2 DATA COLLECTION

The global solar irradiance data were obtained from INMET's platform of automatic stations for the city of Maceió. The downloaded data were related to radiation (KJ m-2) from the automatic station of Maceió (Maceió-A303), which according to INMET is composed of a central memory unit, i.e., a data logger, connected to several sensors of meteorological variables such as atmospheric pressure, temperature, relative humidity, precipitation, solar radiation, wind direction and speed, etc., which integrates the observed values minute by minute and automatically provides them every hour. The data were downloaded from the period Jan/2014 to Dec/2017 totaling 4 years of

data. After being downloaded the data were computed and taken to Microsoft Excel 2007 software in which some corrections were made. A quality control process is essential before using any database of the site of interest. Immediately afterwards, daily averages were taken in order to better characterize the KT.

The solar irradiance at the top of the atmosphere was calculated from the following equation (Eq.1) proposed by Iqbal (1983):

$$Ro = So\ Eo \cos \theta Z \qquad (1)$$

where, So is the solar constant (=1367 W m-2), Eo is the radius vector of the Earth's orbit, and θZ is the zenith angle.

The Earth orbit vector radius (Eo) and zenith angle (θZ) were obtained from the following equations:

$$E_o=1+0{,}033\cos\left(\frac{2\pi dn}{365}\right) \quad (2)$$

$$\cos\theta_z = \text{sen}\varphi\ \text{sen}\delta + \cos\varphi\ \cos\delta\ \cosh \quad (3)$$

where, dn is the sequential day of the year or Julian day (1 to 366), δ is the solar declination, h is the hour angle, and is the local latitude.

The solar declination is expressed in degrees using the equation below (COOPER, 1969):

$$\delta = 23{,}45\ \text{sen}\left[\frac{360}{365}(284+dn)\right] \quad (4)$$

The hour angle (h) was expressed using the following equation:

$$h = 15\,(t-M) + (l_l - l_p) \quad (5)$$

where, t is the local standard time, M is noon, ll expresses the local longitude and lp the standard longitude at the 45° meridian.

Methods and analysis performed

The global atmospheric transmittance adapted from Iqbal (1983), was used to characterize the cloudiness, determined by the ratio between the global solar irradiance and the expected solar irradiance on a horizontal surface at the top of the atmosphere (Ro), i.e:

$$KT = \frac{R_G}{R_o} \quad (6)$$

Thus, when KT values < 0.4, conditions are cloudy or high cloudiness (NB), 0.4 ≤ KT < 0.6, partly cloudy or medium cloudiness (PN), and KT ≥ 0.6, conditions are clear or low cloudiness

(CL). Details of the calculations are described in Iqbal (1983) and Souza, Nicácio and Moura (2005).

KT was calculated for both hourly and daily values. Frequency and cumulative frequency histograms of daily (KTd) and hourly (KTh) global atmospheric transmittance were made with a total of 20 class intervals, in order to analyze seasonal trends, the intervals of higher or lower occurrences, as well as, the periods with higher or lower incidence of solar radiation in the study region. The graphs of RG and

Ro and the histograms of frequency and cumulative frequency of KTd and KTh were prepared through the software Microcal Origin Pro 8.0 considering the interval between 07:00 and 17:00 that comprises almost the entire daytime period and also contributes to the reduction of the cosine error, occurring between sunrise and sunset.

For seasonal analysis of solar radiation and KT conditions the data were separated into two different seasons (periods) according to the climatology of the region. Thus according to Souza et al., 2003, the rainy season, or rainy period, starts in April and ends in July and the dry season, or dry period, starts in November and extends until February.

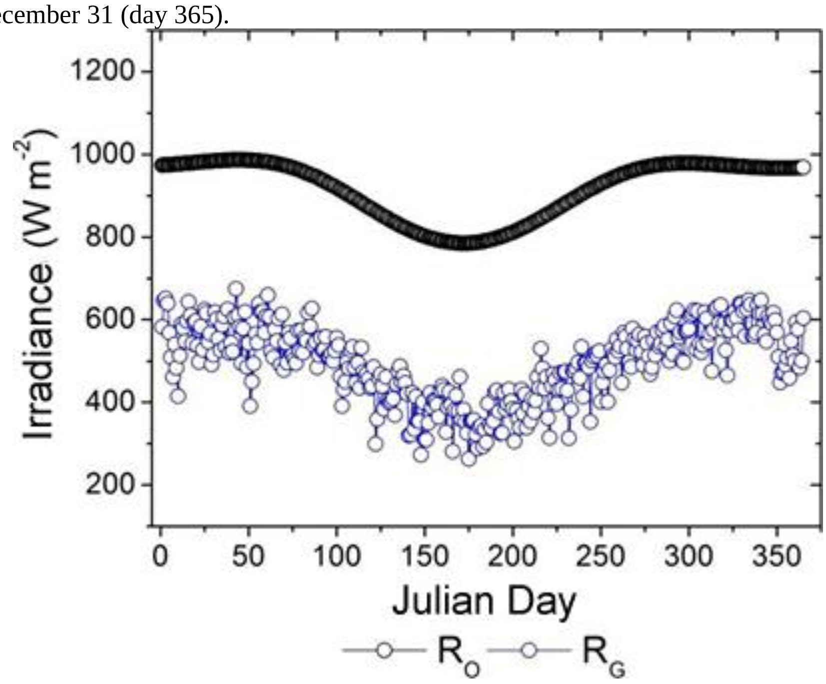
3 RESULTS AND DISCUSSION

3.1 SOLAR IRRADIANCE AT THE TOP OF THE ATMOSPHERE AND GLOBAL

Figure 2 presents the daily distribution of solar radiation at the top of the atmosphere and on the surface throughout the year for the city of Maceió-AL. In that figure it is possible to observe that both irradiance curves follow the expected pattern throughout the year, especially Ro which necessarily already has its values predetermined, with a decrease during winter and increase during summer. This is due to the variation in solar declination during the year, which in turn is influenced by the Earth's tilt axis, allowing the solar disk to move more to the north during winter in the southern hemisphere (rainy season) and causing the solar radiation to have a longer optical path to be traveled until it reaches the surface of the site during this period. During the summer (dry season) the opposite occurs, the solar declination is turned to the south, causing an increase in the incidence of solar radiation in the southern hemisphere. In the case of RG besides being influenced by the axis of inclination of the Earth is also influenced by cloudiness, explaining the fact that there are several oscillations in its curve (PORFÍRIO et al., 2012).

The daily average of Ro was 916.34 W m-2 , its highest value was 986.49 W m-2 on February 14 (day 45) while the lowest value was verified on June 21 (day 172) (785.10 W m-2) coinciding with the day of beginning of the winter solstice in the region. The RG had its maximum value on February 12 (day 43) (674.49 W m-2) and minimum of 262.79 W m-2 on June 24 (day 175). The daily mean RG was 495.42 W m-2 ± 91.53 W m-2 being approximately 54.06 % lower than Ro. The daily average irradiances for the dry season were 976.35 W m-2 and 565.64 W m-2 ± 57.03 W m-2 , respectively, while for the rainy season they were 832.77 W m-2 and 407.41 W m-2 ± 68.83 W m-2 where the RG was 57.93% lower than Ro in the dry season and 48.92 % in the rainy season. This highlights the existence of a greater dependence on cloudiness during the dry season when compared to Ro. Souza, Nicácio and Moura (2005) and Porfirio et al. (2012) found similar variations for Ro and RG irradiances in the same study region, but with mean daily total values. Yohanna, Itodo and Umogbai (2011) observed in the region of Makurdi, Nigeria variation of RG also very similar to that found here, however with much lower annual mean values.

Figure 2. Annual daily mean variation of the solar irradiance at the top of the atmosphere (RO) and annual mean daily variation of the period 2014-2017 of the global solar irradiance (RG) for the region Maceió-Alagoas. Julinao day in ascending order from January 1 (day 01) to December 31 (day 365).

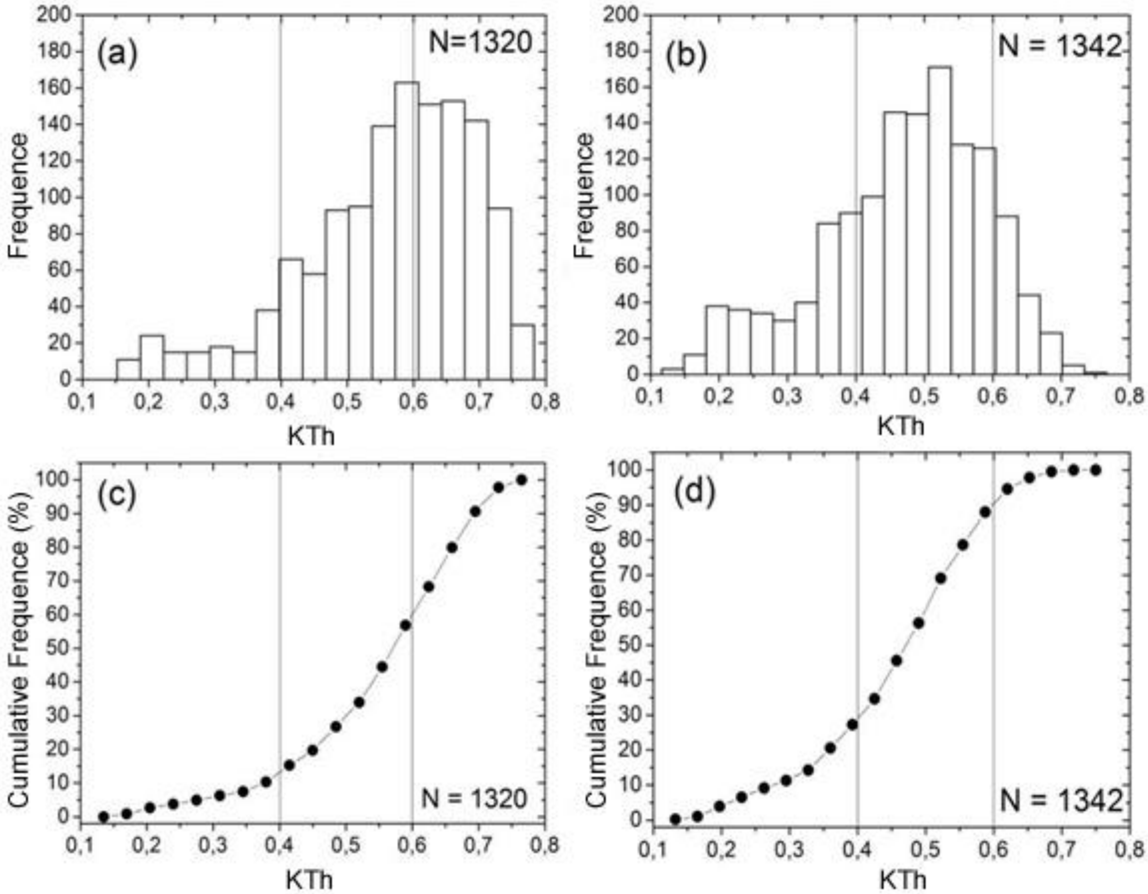


3.2 GLOBAL TIME ATMOSPHERIC TRANSMISSION FREQUENCY (KTh)

The amount of solar radiation reaching the surface can be determined by analyzing the behavior of the global atmospheric transmittance, through frequency histograms and cumulative frequency, as well as the intervals of higher or lower occurrence of KTh, either for the whole year or for each season independently. Thus, it can be seen that the frequency of KTh observed in the dry season (Figure 3a and 3c) had the highest occurrence in partly cloudy sky conditions, equivalent to 46.51% (614) of the total hourly values for this season. Followed by clear sky conditions with 43.19% (570) and cloudy sky conditions with 10.30% (136).

For the rainy season (Figure 3b and 3d) the highest occurrence was also seen under partly cloudy sky conditions which had approximately 60.73 % (815) of the total values. Followed by cloudy sky conditions with 27.27 % (366) and clear sky conditions which had 12 % (161) of the values, i.e. only 12% of the hourly values of the studied period had little or no cloudiness. It is noted a large increase in the values of cumulative frequency under conditions of partly cloudy and cloudy skies compared to the dry season, this fact is expected, since in the rainy season there is a greater presence of cloudiness, especially that which partially covers the sky, ie, time with scattered clouds. In this sense we highlight one of the main factors responsible for cloud formation in the region, the sea breeze phenomenon, this phenomenon is responsible for creating a band of cumulus clouds from the formation of a convergence zone near the coast (breeze front) that acts to contribute to these clouds until about 13:00 hours, when there is the formation of a cumulus suppression area related to the displacement of the areas of subsidence and convergence of the breeze (ROTUNNO et al., 1992; SILVA, 2003)

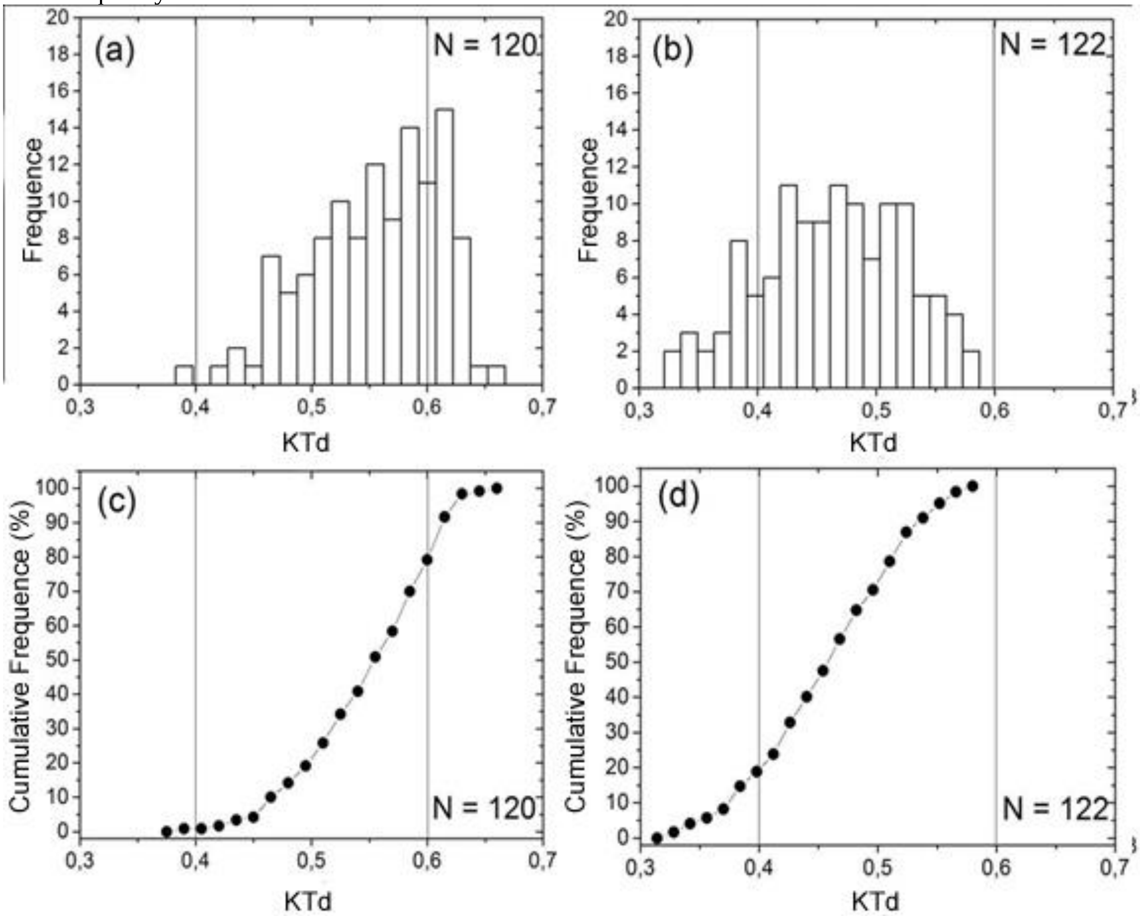
Figure 3. hourly global atmospheric transmittance (KTh) frequency for dry season (a) and rainy season (b) and cumulative frequency (%) of hourly global atmospheric transmittance (KTh) for dry season (c) and rainy season (d). N is the number of values for each frequency.



3.3 DAILY GLOBAL ATMOSPHERIC TRANSMISSION FREQUENCY (KTd)

The frequency of daily KT for the dry season (Figure 4a and 4c) had the highest occurrence in partly cloudy sky conditions with 78.34% (94) of the total data, followed by clear sky conditions with that had 20.83% (25) of the data and cloudy sky conditions with only 0.83% (1). In the case of the rainy season (Figure 4b and 4d) the frequency of values were higher for days with partly cloudy skies equaling 81.15% and lower for cloudy sky days which had 18.85% frequency, had no days with KT above 0.6. Porfirio et al. (2012) and Souza, Nicácio and Moura (2005) found variations of KTd frequency values similar to those presented, mainly for partly cloudy and cloudy sky conditions.

Figure 4: Frequency of daily global atmospheric transmittance (KTd) for dry season (a) and rainy season (b) and cumulative frequency (%) of hourly global atmospheric transmittance (KTd) for dry season (c) and rainy season (d). N is the number of values for each frequency.



3.4 PROBABILITY OF OCCURRENCE OF GLOBAL ATMOSPHERIC TRANSMISSION HOURLY (KTh)

As the levels of solar radiation reaching the surface depend directly on cloud conditions, it is necessary to characterize them in order to determine the real levels of this radiation that is reaching the surface of a given location. Thus, Table 1 shows the annual probability of occurrence, for the dry season and rainy season of a given hourly cloudiness condition in Maceió-AL.

For cloudy sky conditions (KT < 0.4) it can be seen that the annual probability was 18.73%, while in partly cloudy sky conditions (0.4 ≤ KT

< 0.6) the probability rises to 57.21 % and in clear sky conditions (KT > 0.6), 24.06

%. This indicates that much of the daily periods of the year in the study region were partly cloudy, with levels of global solar radiation varying between 60% and 40%. In the case of the dry season the probability of occurrence for cloudy sky conditions was lower with approximately 12.95 %, while for partly cloudy and clear sky conditions the probability was close between the two 46.97 % and 40.08 %, respectively, an increase of approximately 16 % for clear sky conditions compared to the annual probability. In the rainy season the opposite occurred, the probability of occurrence increased significantly for cloudy (28.54%) and partly cloudy (62.30%) sky conditions. Clear sky hours during this season only occurred in 9.17 % of the cases, indicating the low levels of solar radiation reaching the surface during this period.

Table 1. Probability of annual and seasonal occurrence of hourly global atmospheric transmittance (KTh) for the Maceió-Alagoas region.

KT interval	Annual probability (%)	Dry season probability (%)	Wet season probability (%)
KT < 0.4	18,73	12,95	28,54
0.4 ≤ KT < 0.6	57,21	46,97	62,30
KT > 0.6	24,06	40,08	9,17

3.5 PROBABILITY OF OCCURRENCE OF DAILY GLOBAL ATMOSPHERE TRANSMISSION (KTd)

The most occurring daily cloudiness condition for both the year and seasonal periods was partly cloudy sky (Table 2). The annual probability returned a value of 83.29 % of partly cloudy sky occurrences, while in the dry season the values were 78.83 % and in the rainy season 79.51 %. For cloudy sky conditions the annual probability was 8.22%, for the dry season 0.83 % and for the rainy season 20.49

%. And under clear sky conditions the annual probability of occurrence was 8.49%, for the dry and rainy season it was 20.83 % and 0 %, respectively. Through these results one can see that the probability in all cases had its majority situated in partly cloudy sky conditions, even more than in hourly values. This situation can be explained by the fact that when the daily averages are taken, most of the KT values tend to concentrate closer to the median, since in the hourly values there were more data under cloudy and clear sky conditions, which during each day ended up being decreased or increased depending on the local weather conditions.

Table 2. Annual and seasonal probability of occurrence of daily global atmospheric transmittance (KTd) for the Maceió-Alagoas region.

KT interval	Annual probability (%)	Dry season probability (%)	Wet season probability (%)
KT < 0.4	8,22	0,83	20,49
0.4 ≤ KT < 0.6	83,29	78,33	79,51
KT > 0.6	8,49	20,83	0,00

4 CONCLUSIONS

The curve of the global solar irradiance had normal characteristics taking into account the conditions of location, climate and cloudiness of the region, i.e. maximum values during the dry season and minimum values during the rainy season. The maximum and minimum values of the global solar irradiance were on days close to the solar irradiance at the top of the atmosphere, without much oscillation during the year. Through the frequency analysis of the global atmospheric transmittance in the region it can be seen that both on the hourly and daily time scales, the values are always mostly located under partly cloudy sky conditions, either during the dry or rainy season, however in the rainy season, if compared to the dry season, the frequency tends to be much higher for partly cloudy sky conditions and as expected for cloudy sky conditions. The annual and seasonal occurrence probabilities showed this character, because for the whole year and for the dry and rainy season the probability of occurrence of hours and days under partly cloudy conditions is high, and only in the dry season for hourly values the probability stays below 50% for these conditions.

Thus, the study region was characterized with partly cloudy conditions, i.e., $0.4 \leq KT < 0.6$ concluding that the global solar radiation in the region throughout the year has a greater chance of being less than 60% of the total solar radiation reaching the top of the atmosphere and reasonable chances of being below 40% or above 60% throughout the year, these chances increase when the period of the year changes.

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